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16. ABSTRACT The paper is a brief discussion and summary of state-of-the-art combustion modification NOx control technology for boilers and industrial process combustion equipment. These combustion modification techniques, when properly applied, offer the potential for cost-effective NOx control for the major fossil-fuel-fired stationary combustion sources in the near term. NOX, principally NO and NO2, are atmospheric pollutants with potential for adverse effects on human health and welfare. Fuel combustion contributes about 99% of technology-related NOx emissions. Because of human activities in urban areas, NOx concentrations are frequently 10 to 100 times higher there than in nonurban areas. NOx enters into complex atmospheric photochemical reactions in the presence of hydrocarbons and results in the formation of undesirable secondary species. Also, recent studies indicate that NOx contributes to the formation of acid precipitation. The effects of NO2 were among the factors leading to the passage in the U.S. of the 1970 Clean Air Act and succeeding amendments which require the control of pollutant emissions to protect human health and welfare. The U.S. EPA has established regulatory standards for NOx, as well as for other pollutants, from a range of sources. These regulations have prompted efforts to identify and evaluate the performance of effective controls for NOx emissions.

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STATE-OF-THE-ART COMBUSTION MODIFICATION NO_x CONTROL FOR STATIONARY COMBUSTION EQUIPMENT

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ABSTRACT

Nitrogen oxides (NO_x), principally nitric oxide (NO) and nitrogen dioxide (NO_2), are atmospheric pollutants having potential for adverse effects on human health and welfare. Fuel combustion contributes about 99 percent of technology-associated NO_x emissions. Because of human activities in urban areas, NO_x concentrations are frequently 10 to 100 times higher there than in nonurban areas. NO_x enters into complex atmospheric photochemical reactions in the presence of hydrocarbons and results in the formation of undesirable secondary species. Also, recent studies indicate that NO_x contributes to the formation of acid precipitation. The effects of NO_2 were among the factors leading to the passage in the United States of the Clean Air Act of 1970 and succeeding amendments which require the control of pollutant emissions to protect human health and welfare. The U.S. Environmental Protection Agency (EPA) has established regulatory standards for NO_x, as well as for other pollutants, from a range of sources. These regulations have prompted an extensive effort on the part of industry, equipment manufacturers, various research organizations, and governmental agencies to identify and evaluate the performance of effective controls for NO_x emissions. This paper presents a brief discussion and summary of state-of-the-art combustion modification NO_x control technology for boilers and industrial process combustion equipment. These combustion modification techniques, when properly applied, offer the potential for cost-effective NO_x control for the major fossil-fuel-fired stationary combustion sources in the near term.

INTRODUCTION

Surveys of approaches for the control of NO_x from combustion sources have indicated that the most cost-effective technologies are based on changing the combustion process to minimize the formation of NO_x. These "combustion modification" technologies have consequently been given highest priority for development and application in the United States. Other techniques, such as denitrification of fuels and flue gas treatment for NO_x control, have also been considered. These latter methods so far have not received wide acceptance in the United States, due to their higher costs.

In the combustion process NO_x is formed by two mechanisms. "Thermal NO_x" is formed from the reaction of nitrogen and oxygen in the combustion air at elevated temperatures. "Fuel NO_x" is formed from nitrogen that is chemically bound in the fuel which reacts with oxygen.

COMBUSTION MODIFICATION TECHNIQUES

Of the numerous combustion modification techniques investigated, only a few have been found to have effective applicability to the wide range of sources

requiring NO_x emissions control. The techniques which have proved effective and are being applied commercially in the United States are discussed below, and primarily depend on lowering the maximum flame temperature achieved in the combustion reaction along with operating in an oxygen deficient mode as long as possible in the furnace zone.

Low excess air

In the late 1950's low excess air (LEA) firing was explored as a means for improving operating conditions on oil-fired boilers in the United Kingdom (ref. 1). LEA firing reduces the local flame zone oxygen concentration thus reducing both "thermal" and "fuel" NO_x formation. LEA firing is easy to implement and increases thermal efficiency. Low temperature corrosion, air heater plugging, furnace slagging, and heating surface fouling were all reduced as a result of LEA (ref. 2, 3, 4) firing.

Staged combustion

During California tests in the late 1950's, it was found that staged combustion to achieve delayed mixing of the fuel and air, especially when combined with LEA firing, resulted in further NO_x reduction (ref. 5). Staged combustion provides a portion of the combustion air to be introduced with the fuel so that initial combustion occurs under fuel-rich conditions (with less than the stoichiometric amount of air). The remainder of the combustion air, required for complete combustion and carbon burnout, is introduced at a later stage. Staged combustion can be achieved in several ways. For retrofit applications the most common approach is to use burners out of service. In a multiburner boiler, the top burners can be operated with air-only while the lower burners are operated fuel-rich. If removal of burners from service creates problems with maintaining load, staged combustion can be achieved by biased firing, with the top burners operated air-rich, and the lower burners, fuel-rich. For new designs or for extensive modifications of existing boilers, overfire air ports may be added above the top burner row. Thus by operating the burners fuel-rich and adding air through the overfire air ports to complete burnout, staged combustion can be achieved for NO_x control. The effect of two-staged combustion on NO_x is explainable: first, there is a lack of available oxygen for complete chemical oxidation in the first stage which is operated substoichiometrically; and second, flame cooling in the primary zone reduces peak temperature.

Flue gas recirculation

Another technique used for controlling NO_x is flue gas recirculation. Flue gas injected into the primary flame zone has the effect of diluting the combustion air and of decreasing the adiabatic flame temperature and the oxygen level. For the past 25 to 30 years, flue gas recirculation, in which a portion of the flue gas is introduced into the hopper near the bottom of the furnace, has been

used in large boilers as a means of controlling superheat temperatures. Based on laboratory tests, flue gas recirculation into the burner zone became a primary technique for controlling NO_x from fuels with a relatively low fuel nitrogen content; e.g., natural gas and oil.

Water or steam injection

When firing gas or oil, water or steam injection also has been used to control NO_x by decreasing the adiabatic flame temperature. But the quantities of water or steam needed to achieve the desired effect may create undesirable operating conditions such as a decrease in efficiency or an increase in corrosion rates. Field tests have shown the decrease in efficiency to be so severe that this approach is not very practical. However, a variation of this technique, the firing of water/oil emulsions, is more promising. Recent tests on industrial package boilers (ref. 6, 7) have shown that fuel oil emulsions with up to 18 percent water can significantly reduce particulate emissions. Also, there is potential for a slight increase in efficiency, especially when the percentage of water is low. With distillate oil, NO_x emissions are reduced about 15 percent, but with residual oil there is a limited effect on NO_x due to higher fuel nitrogen.

Reduced air preheat

Reducing combustion air preheat can also reduce NO_x as the adiabatic flame temperature is decreased. However, it can result in decreased efficiency. For this reason, it is desirable to use economizers in place of air preheaters, where practical. Economizers are heat recovery devices designed to transfer heat from the products of combustion to a fluid, usually the boiler feedwater.

Load reduction

Load reduction can also be used to reduce NO_x emissions. Load reduction reduces heat input into the furnace so that both heat release rate and peak flame temperature are reduced. However, the reduced mass flow through the burners often causes improper fuel/air mixing, thus creating smoke and CO problems. To alleviate this situation excess air is increased which increases NO_x. The net effect may be no change in NO_x. A more desirable way to achieve a reduction in combustion intensity would be to increase the size of the firebox and increase burner spacing on new boiler designs.

Low NO_x burner designs

Low NO_x burners are a relatively recent development for NO_x control. By redesigning the burner for controlled mixing of air and fuel, NO_x emissions can be controlled. Several approaches are being investigated. Good mixing and divided flame burners primarily reduce thermal NO_x by increasing flame quenching or heat dissipation. Self-recirculating burners recycle combustion gas into the combustion zone, and staged combustion burners inject substoichiometric air into the

primary combustion zone with excess air added downstream (later). Both thermal and fuel NO_x are reduced by these latter two designs.

Ammonia injection

Noncatalytic reduction of NO_x with ammonia (NH_3) injection is also being investigated. A process has been patented under the tradename "Thermal De NO_x" by Exxon Research and Engineering Company (ref. 8), and laboratory tests have shown NO_x reductions as high as 90 percent (ref. 9). However, field tests have resulted in NO_x reductions close to 40 percent. This approach works by reacting the combustion formed NO with NH_3 to yield molecular nitrogen and water vapor in a fairly narrow gas temperature range. The narrow temperature "window," sensitivity to residence time, geometry of boiler convective section, by-product emissions, and costs, are all definite limitations of this technique.

In-furnace NO_x reduction

A relatively new concept for NO_x reduction is in-furnace NO_x reduction, also known as reburning or staged fuel injection. This technique was investigated in the United States on a laboratory scale in the early 1970's by Wendt and Sterling. It is being developed for commercial use by Mitsubishi Heavy Industries (ref. 10). The concept uses two separate zones for combustion. The stoichiometry in the first zone has little effect on final NO_x emissions, but the second zone is operated substoichiometrically (fuel rich) to reduce previously formed NO_x. Overfire air is then injected downstream of the second combustion zone to complete the combustion. Gas, oil, or coal fuel can be used in this process, and only about 10 percent of the fuel needs to be used in the second combustion zone for effective NO_x reduction. To date, tests have shown that NO_x reductions of about 50 percent are achievable in the second combustion zone, and this is in addition to levels achieved in the first zone which may use low NO_x burners.

STATE-OF-THE-ART CONTROL TECHNIQUES

The state-of-the-art NO_x control techniques, relied on in the past to achieve significant NO_x reductions, were based generally on changes in operating conditions or on relatively minor changes in combustion equipment design. These techniques were evaluated through field testing to determine the degree of NO_x emissions reduction achievable. This information has been made available to potential users of the technology and has frequently been used as a basis for regulatory levels of NO_x emission standards. Details regarding many of these techniques applicable to specific equipment types are given in the following sections.

Utility boilers

In 1970, field tests of stationary combustion equipment were initiated to determine the effect of combustion modification techniques on emissions. Although primary emphasis was placed on NO_x, other combustion related emissions (e.g., CO,

HC, and particulate) were also of interest. Based on a NO_x systems study (ref. 11) performed by Exxon in the late 1960's, emphasis was placed on testing utility boilers. It was found that variation of excess air, staged combustion, flue gas recirculation, and burner tilt could be used to reduce NO_x emissions by up to 80 percent for gas- and oil-fired boilers. The degree of effectiveness varied with boiler design characteristics. With gas-fired boilers operated at full load, the average NO_x emission was 589 ppm (corrected to 3 percent O_2, dry basis); here it was possible to reduce NO_x by an average of 64 percent. With oil-fired boilers NO_x was reduced by approximately 40 percent from a baseline of 360 ppm.

NO_x emissions from coal-fired boilers averaged 994 ppm. Initial tests indicated that application of combustion modification to coal firing was more difficult than for gas or oil firing. Problems included the potential for slagging, fouling, and corrosion. Also, there was a hesitancy by boiler operators to use combustion modification on coal-fired boilers. Initial tests were run with small incremental operational changes, and NO_x reductions as high as 50 percent were achieved. It was clear, though, that additional tests were needed to properly evaluate the use of combustion modification techniques on coal-fired installations.

For this reason, since 1972, utility boiler field tests sponsored by EPA, and in part co-sponsored by the Electric Power Research Institute (EPRI), have emphasized coal-fired units. Gaseous emissions, particulate emissions, and furnace tubewall corrosion rates were measured, and engineering information on boiler operability was determined. From 1972 to 1979, 22 pulverized-coal-fired boilers were tested, ranging in size from 100 to 800 MW (ref. 12, 13). As shown in Table 1, NO_x reductions of 12 to 62 percent were achieved, depending on the unit and its flexibility for combustion modification. The average NO_x reduction for all units was 37 percent. Low excess air combined with staged combustion was found to be an effective means for controlling NO_x emissions from coal-fired utility boilers. Side effects such as increased particulate emissions, increased carbon content of the flyash, slagging, and fouling were not significant. The only area of concern was that of tubewall corrosion rate measurement since only corrosion probes were used to measure corrosion rates. Preliminary short-term (300 hr) tests with corrosion probes did not indicate that corrosion was a problem.

The combustion variables pertinent to the studies include the effects of load variation, low excess air firing, staged combustion, air preheat temperature, burner tilt, and secondary air register settings. In later tests the effectiveness of equipment modifications designed to provide NO_x emission control was explored; e.g., the use of overfire air ports and a low NO_x burner design. Also, a long term (2 year) study to determine the effect of combustion modification on tubewall corrosion was initiated. Corrosion probes, corrosion test panels welded into the boiler, and ultrasonic thickness mapping of the furnace tubewalls were all used. Wall thickness measurements revealed that the

TABLE 1

Summary of coal and mixed fuel fired boilers tested

Station and Boiler No.	Boiler Mfr.[a]	Type of Firing[b]	Fuel Burned[c]	MCR[d] (Mwe)	No. of Burners	NO_x Emissions: Baseline[e] ng/J	Baseline[e] (lb/10^6 Btu)	Baseline[e] ppm	Low NO_x[e] ng/J	Low NO_x[e] (lb/10^6 Btu)	Low NO_x[e] ppm	% NO_x Reduction[f]	Comments
Widows Creek-6	B&W	RW	C	125	16	370	0.96	634	221	0.52	379	40	g
Crist-6	F-W	FW	C	320	16	486	1.13	832	321	0.75	550	34	g
Harllee Branch-3	B&W	HO	C	480	40	415	0.97	711	270	0.63	463	35	g,h
Four Corners-4	B&W	HO	C	800	54	546	1.27	935	285	0.66	488	48	g,h
Naughton-3	CE	T	C	330	20	310	0.72	531	128	0.30	219	59	g,h
Barry-4	CE	T	C	350	20	242	0.56	415	159	0.37	273	34	g,h
Barry-3	CE	T	C	250	48	239	0.56	410	181	0.42	310	24	
Big Bend-2	RS	Turbo	C	350	24	350	0.82	600	232	0.54	398	34	
E.D. Edwards-2	RS	FW	C	256	16	411	0.96	703	210	0.49	359	49	
Leland Olds-1	B&W	HO	C	218	20	332	0.77	569	219	0.51	375	33	
Dave Johnston-2	B&W	FW	C	105	18	265	0.62	454	125	0.29	214	53	
Dave Johnston-4	CE	T	C	348	28	253	0.59	434	224	0.52	384	12	
Widows Creek-5	B&W	RW	C	125	16	349	0.81	597	273	0.64	468	22	g,h
E.C. Gaston-1	B&W	HO[i]	C	270	18	227	0.53	389	162	0.38	278	29	g,h
E.C. Gaston-1,2						345	0.80[j]	591	162	0.38[j]	278	53	j
Barry-2	CE	Tk	C/G	130	16	199	0.46	341	110	0.26	189	45	
Morgantown-1	CE	T	C/O	575	40	322	0.75	552	235	0.55	403	27	
Navajo-2	CE	Tk	C	800	56	287	0.67	492	165	0.38	282	43	g,h
Comanche-1	CE	Tk	C	350	20	244	0.57	417	152	0.35	261	37	g,h
Mercer-1	F-W	FW[l]	C	270	24	808	1.88	1393	512	1.19	876	37	g,h
Cooper-2	B&W	FW	C	220	18	325	0.76	557	282	0.66	483	13	g,h
Comanche-2	B&W	HO	C	350	32	424	0.99	726	162	0.38	278	62	g
Crist-7	FW	HO	C	500	24	584	1.36	1000	377	0.88	645	36	g,h

a B&W - Babcock and Wilcox
CE - Combustion Engineering
F-W - Foster Wheeler
RS - Riley Stoker

b HO - Horizontally opposed
T - Tangential
RW - Rear wall
FW - Front wall
Turbo - Turbo-furnace

c C - coal, C/G - coal/gas mixed, C/O - coal/oil mixed (only coal-fired results are reported)

d MCR - Maximum continuous rating

e PPM NO_x - 3% O_2, dry basis

f % NO_x reduction at full or near full load

g Particulate tests performed on these boilers

h Corrosion probe tests performed on these units

i Special low NO_x burners

j E.C. Gaston No. 2 is a sister unit to Gaston No. 1 and is equipped with conventional burners

k Overfire air ports

l Wet bottom furnace

boiler walls in the burner zone lost 5 mils/yr under staged-combustion low-NO_x conditions compared to 4 mils/yr under baseline conditions. In the non-burner zone the corrosion rate was 2.1 mils/yr under low NO_x conditions, compared to 5.3 mils/yr under baseline conditions. Therefore, the corrosion rates experienced during extended low NO_x operation would not appear to appreciably reduce the expected useful life of the furnace tubes.

In Table 1, low NO_x emissions are defined as the best combination of combustion modifications that could be utilized at or near rated capacity of the boiler, and without incurring significant adverse side effects in short term tests. The greatest NO_x reductions were obtained by using a combination of low excess air and staged combustion. Units with special low NO_x design features (e.g., overfire air ports, low NO_x burners) are indicated in the table.

As shown in Table 1, tangentially fired boilers are inherently lower emitters of NO_x than other firing designs. However, the percent NO_x reduction response of different firing designs to combustion modification is very similar, averaging from 35 to 40 percent compared to baseline emissions.

Similarly, the Babcock and Wilcox (B&W) dual register low NO_x burners (E.C. Gaston-1) are effective for low NO_x operation. Also, all units tested with built-in overfire air ports resulted in low NO_x operation. It should be noted that without overfire air ports, staged combustion via burners-out-of-service can often only be achieved at the expense of a 10 to 15 percent load reduction.

In another study (ref. 14), the 560 MW Hatfield No. 3 boiler was tested for EPRI by KVB, Inc. This horizontally opposed coal-fired boiler was tested to determine the effect of burners-out-of-service and flue gas recirculation (FGR) on NO_x emissions. Baseline NO_x of about 900 ppm were reduced by 35 percent with 10 of the 40 burners on air only. NO_x emissions were reduced by only 17 percent with 15 percent FGR. Thus, FGR is not a cost-effective means for controlling NO_x from coal-fired boilers. This result was expected since FGR affects only thermally formed NO_x, and most NO_x from coal-firing results from fuel nitrogen. In addition to the techniques described above, both EPA and EPRI are interested in determining the potential for in-furnace NO_x reduction, or reburning, on utility boiler NO_x emissions. The primary concerns to be addressed are to determine whether in-furnace NO_x reduction is applicable to U.S. designed boilers, and whether it can be retrofitted to existing boilers.

Industrial boilers

In 1973, EPA initiated a 2-year field test study with KVB, Inc., to determine the effect of combustion modification on industrial boilers ranging in capacity from 3 to 146 MW (10,000 to 500,000 lb steam/hr) (ref. 15, 16). NO_x emissions were found to be slightly dependent on boiler size, but they were strongly dependent on type and nitrogen content of the fuel being fired. This strong de-

pendence is illustrated in Table 2, which shows the range and average concentration of NO_x emissions under normal (baseline) and low NO_x operating conditions. Approximately 70 boilers were tested. As expected, coal was the chief emitter of NO_x.

TABLE 2

Range and average emissions of total NO_x at baseline and at low-NO_x operation for industrial boilers

	Range	Average Emissions			
	Baseline	Baseline Operation		Low NO_x Operation	
Fuel Type	NO_x ng/J (ppm @ 3% O_2)	NO_x ng/J (ppm @ 3% O_2)	O_2 %	NO_x ng/J (ppm @ 3% O_2)	O_2 %
Coal	100-562 (164-922)	290 (475)	8.7	225 (369)	6.7
No. 2 Oil	36-101 (65-180)	67 (120)	5.5	59 (105)	4.0
No. 5 Oil	112-347 (200-619)	164 (293)	5.8	142 (254)	4.9
No. 6 Oil	107-196 (190-350)	151 (269)	5.3	121 (216)	4.9
Natural Gas	26-191 (50-375)	71 (139)	4.8	57 (111)	5.0

It was found that combustion modification for NO_x control did not increase the other gaseous emissions to any extent, but it did have a significant effect on the particulate emissions and on the boiler heat-loss efficiency. The limit to which any combustion modification method could be applied was that at which the CO emissions would not exceed about 34 ng/J (100 ppm), because in most instances CO levels increase rapidly beyond this point.

The effects on NO_x, boiler heat-loss efficiency, and particulate concentrations are summarized for all of the combustion modification methods in Figures 1 and 2 (ref. 16). Each chart is divided into quadrants, two of which are labeled Best Quadrant and Worst Quadrant. With respect to NO_x and boiler efficiency, the criterion for the best quadrant is that the NO_x emissions decrease but the efficiency increases. In the worst quadrant the opposite occurs. With solid particulates, both the NO_x and particulate emissions decrease in the best quadrant.

Excess combustion air. The best combustion modification method (on the basis of ease of implementation, emission reduction, and efficiency) was to reduce the amount of excess air being fired. In about 72 percent of the cases where the excess air was reduced, the NO_x emissions decreased by up to 38 percent of the baseline level, and the efficiency increased by up to 3 percentage

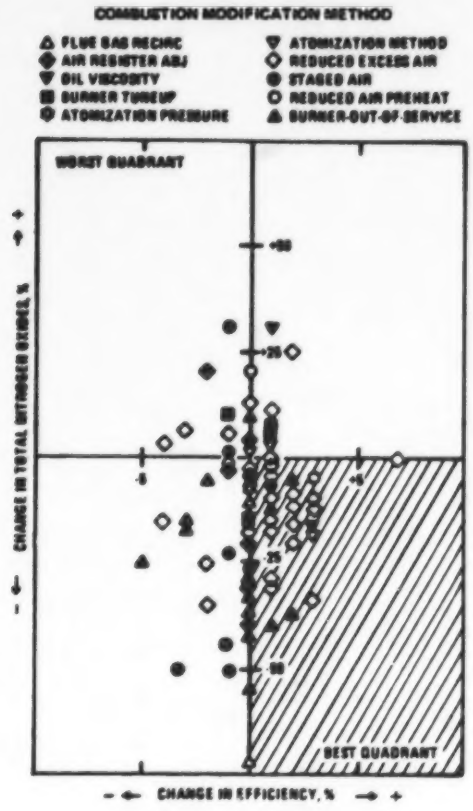

FIGURE 1. EFFECT OF COMBUSTION MODIFICATION METHOD ON TOTAL NITROGEN OXIDES EMISSIONS AND BOILER EFFICIENCY.

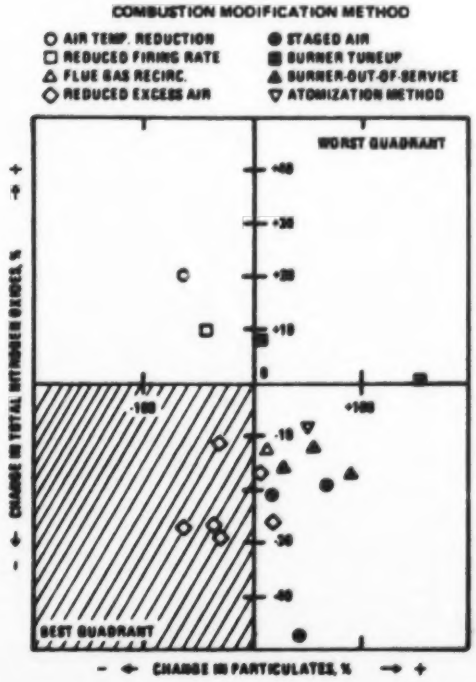

FIGURE 2. EFFECT OF COMBUSTION MODIFICATION METHOD ON TOTAL NITROGEN OXIDES AND SOLID PARTICULATE EMISSIONS.

points (e.g., from 75 to 78 percent). The effect of reducing the excess air was greatest for coal fuel, causing a reduction in NO_x level of about 12 percent for each percentage point reduction in oxygen.

The effect on the solid particulate emissions was to reduce them by up to 15 percent with coal fuel and up to 30 percent with No. 6 oil fuel. The criterion for minimum excess air was that CO emissions not exceed 100 ppm: with this criterion, in no case did the particulate increase.

Staged combustion air. Nine tests were run where the combustion air was added in stages: three each on coal, oil, and gas fuels. In all but two cases, staging the air reduced the NO_x emissions by up to 47 percent. The exceptions were natural gas fuel, where the change was zero, and a spreader stoker, where NO_x emissions increased by 10 percent. In four cases, the boiler efficiency decreased up to 3 percentage points, and in the other five cases it was unchanged.

On three of the staged air tests with No. 6 oil, the particulate concentration was measured with and without staged air, and in all cases the particulate emissions increased by 12 to 75 percent. Apparently, delaying complete combustion increased the amount of unburned carbon in the flue gas.

On a 20 MW (70,000 lb/hr) natural-gas-fired boiler that had three burners in a horizontal row, it was possible to lower the NO_x emissions from the baseline level of 108 ng/J (211 ppm) to 85 ng/J (166 ppm) by simply reducing the amount of excess air with no burners out of service. When the center burner was taken out of service, it was possible to enter the fuel-rich burning region and reduce the NO_x emissions to 49 ng/J (96 ppm), for a 55 percent NO_x reduction. The boiler efficiency was unaffected. Similar results were obtained with oil and coal fuels, the reduction in NO_x ranging from 20 to 40 percent.

Other combustion modification techniques and combinations. Staged combustion, variable excess air, and variable air preheat were evaluated while firing natural gas or No. 6 oil in a watertube boiler rated at 16 MW thermal input (55×10^6 Btu/hr). In a watertube boiler rated at 6.5 MW (22×10^6 Btu/hr), flue gas recirculation, staged combustion, and variable excess air were evaluated while firing natural gas, No. 2 oil, and No. 6 oil. Results of these tests are shown in Tables 3 and 4 (ref. 17, 18). Both of these boilers were modified to provide staged combustion by adding part of the combustion air downstream of the burner. The smaller unit was also modified for flue gas recirculation.

Reductions in NO_x emissions of between 70 and 80 percent with natural gas fuel were observed for the two modified industrial boilers tested. These reductions resulted in NO_x emission levels of between 10 and 26 ng/J (20 and 50 ppm at 3 percent O_2, dry) and were achieved with the use of various combinations of all combustion modifications tested. With the exception of lowered air preheat, these reductions were achieved with only slight changes in efficiency and no

TABLE 3

NO_x reduction and efficiency change for combustion modification techniques on a 16 MW (thermal) industrial boiler

	Natural Gas	No. 6 Oil (0.31% N)[a]
Baseline NO_x, ng/J (ppmV at 3% O_2)	82.1 (161)	160 (286)
Combustion Modification Technique	**NO_x Reduction, Percent of Baseline**	
Lowered O_2	6	21
Lowered Air Preheat (LAP)	24	9
Staged Combustion Air (SCA), Normal O_2	31	33
SCA, Low O_2	--	42
LAP + SCA	70	--
Baseline Efficiency, %	81.2	84.8
Combustion Modification Technique	**Change in Efficiency, Percent**	
Lowered O_2	+0.2	+0.8
LAP	-1.0	-2.8
SCA	-0.4	+0.2
LAP + SCA	-3.2	--

[a]Fuel oil nitrogen content, percent by weight.

apparent detrimental changes in other emissions. With lowered air preheat, efficiency was reduced about 3 percent.

On the one boiler tested with No. 2 oil, NO_x reductions of about 75 percent were observed with the use of flue gas recirculation and reduced excess air. These reductions resulted in NO_x levels on the order of 14 ng/J (25 ppm at 3 percent O_2, dry) and were obtained with an increase in efficiency of about 1 percent (neglecting fan power requirements). Reductions in NO_x with No. 6 oil were not as dramatic as for the other fuels. However, it was significant that a 55 percent reduction could be achieved with the combined use of flue gas recirculation, staged combustion, and lowered excess air.

The use of flue gas recirculation can result in flame instability, but it was found that these problems could be resolved by relocating the fuel injection point to areas where flue gas is not fully mixed with air. This technique requires that the flue gas be only partially mixed (and stratified) in the burner throat as opposed to the more common method of complete mixing in the windbox (ref. 19).

TABLE 4

NO_x reduction and efficiency change for combustion modification techniques on a 6.5 MW (thermal) industrial boiler

	Natural Gas		No. 2 Oil	No. 6 Oil
	Ring[a]	Gun[a]	(0.00% N)[b]	(0.20% N)[b]
Baseline NO_x, ng/J (ppmV at 3% O_2)	49 (96)	47 (92)	62 (110)	124 (221)
Combustion Modification Technique	**NO_x Reduction, Percent of Baseline**			
Lowered O_2	19[c]	3.3	20	30
Staged Combustion Air (SCA), Normal O_2	32	46	30	29
SCA, Low O_2	42	--	44	42
Flue Gas Recirculation (FGR), Normal O_2	--	77	68	11
FGR, Low O_2	--	79	73	40
FGR + SCA, Normal O_2	--	76	69	53
FGR + SCA, Low O_2	--	d	77	55
Baseline Efficiency, %	78.2	82.6	82.5	82.5
Combustion Modification Technique	**Change in Efficiency, Percent**			
Lowered O_2	-1.2[c]	+0.9	+1.5	+1.5
SCA, Normal O_2	+0.1	+0.3	+0.9	+0.1
SCA, Low O_2	+0.5	--	+1.1	+0.8
FGR, Normal O_2	--	-0.8	-1.9	-0.7
FGR, Low O_2	--	-0.4	+0.9	+0.6
FGR + SCA, Normal O_2	--	-0.5	-1.2	-0.8
FGR + SCA, Low O_2	--	d	-0.8	+0.1

[a]Burner type.
[b]Fuel oil nitrogen content, percent by weight.
[c]NO_x reduction occurred at increased O_2 level.
[d]Stability limit prevented lowering O_2.

The degree of the NO_x reductions achieved with natural gas and oil fuels is very encouraging for the prospects of controlling NO_x emissions from industrial size boilers. However, between the two boilers tested, the differences in NO_x emissions and reductions achieved indicate that important unit-to-unit variations exist in terms of the relative effectiveness of these NO_x control methods. Therefore, the specific reductions obtained should not be interpreted as achievable on all industrial boilers.

Several field test studies have been performed on coal-stoker-fired industrial boilers sponsored by EPA, U.S. Department of Energy, and the American Boiler Manufacturers Association (ref. 20, 21, 22, 23). The primary finding relative to NO_x control is that combustion modification on existing boiler designs is of limited effectiveness. By using a combination of low excess air

firing with varying overfire air conditions, NO_x reductions of up to 20 percent have been achieved. However, the extent of NO_x reduction can vary widely depending on boiler design and coal characteristics. In order to achieve significant NO_x reductions for coal-stoker-fired boilers, extensive design modifications will be necessary. An ongoing study is being performed for EPA by KVB, Inc. on stokers in which overfire air injection location and amount are being optimized for NO_x control.

Industrial process equipment

Based on the success achieved in controlling NO_x emissions through combustion modification on utility and industrial boilers, it was decided to extend this technology to industrial process combustion equipment. In an EPA-sponsored study of the applicability of minor combustion modifications (ref. 24, 25), KVB, Inc., tested 22 units. A brief summary of NO_x emissions, reductions, and control methods is shown in Table 5. In general, the results indicate that combustion modifications can be applied to industrial combustion equipment, but the reductions achievable vary significantly for different types of devices. Reductions in NO_x of up to 69 percent were observed; however, on many devices, reductions were less than 10 percent. Selection of representative industrial combustion devices was difficult because of the limited amount of information available. Effort should be directed to the further study of the types of devices in the industries considered.

Natural draft petroleum process heaters appear to be low NO_x emitters on an individual basis. However, as a group, they constitute a large fraction of industrial NO_x emissions. Simple combustion adjustments were found to be of limited effectiveness for NO_x emissions reduction or combustion efficiency improvements. However, the use of staged combustion air via air lances through the floor of a 16 MW vertical cylindrical natural draft crude heater resulted in significant NO_x reduction. The unit, which was capable of a throughput of 108 m^3/hr of crude oil, had a baseline NO_x emission level of 66 ng/J (125 ppm at 3 percent O_2) while firing refinery gas. At 4 percent O_2, NO_x was reduced by 60 percent below baseline using the staged air modification. When the stack O_2 was reduced to 2 percent, NO_x was reduced by 71 percent from baseline and heater thermal efficiency was increased by about 3 percent. When firing a combination of 50 percent refinery gas and 50 percent residual oil at 4 percent stack O_2, NO_x was reduced by 34 percent below a baseline of 115 ng/J (214 ppm at 3 percent O_2) by using staged air. At 2 percent stack O_2 this improved to a 53 percent NO_x reduction and thermal efficiency was increased by about 3 percent. Long term (30-day) evaluation of the staged air system revealed no special operating difficulties. This staged air system is expected to be applicable to most types of refinery heaters, whether forced draft or natural draft and whether vertically or horizontally fired.

TABLE 5

Industrial combustion units tested and summary of results

	Fuel	Average Baseline NO_x ng/J[a]	Average Baseline NO_x ppm @ 3% O_2	Maximum Percent Reduction in NO_x	Combustion Modification[b]
Natural Draft Process Heater	Ref. Gas	59	116	18	4 of 32 BOOS
Natural Draft Process Heater	Ref. Gas	50	97	22	Air Register Adjust
Natural Draft Process Heater	Ref. Gas	39	76	21	High Load, Low O_2
Natural Draft Process Heater	Ref. Gas	52	103	8	2 of 16 BOOS
Natural Draft Process Heater	Ref. Gas	49	98	27	Air Register Adjust
Forced Draft Heater, Air Preheat	Ref. Gas	163	320	0	Baseline is Lowest NO_x
	No. 6 Oil	113	222	0	Baseline is Lowest NO_x
Forced Draft Heater, No Air Preheat	Ref. Gas	109	214	67	Low O_2
	No. 6 Oil	97	172	15	Low O_2
Clay Tunnel Kiln	Nat. Gas	46	90	41	Low O_2
Rotary Cement Kiln (Dry Process)	Nat. Gas NG+Coke	903	1460	27	Fuel Switch, Gas to Coke
Rotary Cement Kiln (Wet Process)	Nat. Gas	1319	2250	14	Low O_2, High Air Temp.
Steel Open Hearth Furnace	NG + No. 6 Oil	1094	2070 (Avg)	40	Low O_2
Steel Reheat Furnace	Nat. Gas	56	110	43	3 of 27 BOOS
Steel Soaking Pit	Nat. Gas	52	101	69	Low O_2
Aluminum Melter	Nat. Gas	49	96	0	Low O_2 (NO_x increased)
	No. 2 Oil	104	185	0	Low O_2 (NO_x increased)
Black Liquor Recovery Boiler	Liquor	35	52	30	Secondary Air Adjust
Wood Bark Boiler	Wood+NG	124	229	23	1 of 4 BOOS
Wood Bark Boiler	Wood+Coal	188	300	15	Low O_2
CO Boiler	CO Gas	147	126	12	Air Register Adjust
Natural Gas Engine	Nat. Gas	1020	1990	20	Fuel, Air Adjust
Diesel Engine	No. 2 Oil	904	1611	19	Low Inlet Air Temp.
Gas Turbine Combined Cycle	Ref. Gas	59	118	14	1 of 8 BOOS
Gas Turbine Combined Cycle	Ref. Gas	52	103	38	4 of 16 BOOS

[a] 1 lb/10^6 Btu = 430 ng/J

[b] BOOS = Burners out of service

Forced draft process heaters produced higher NO_x emissions than did natural draft heaters, particularly with combustion air preheat (ref. 26). Reducing excess air reduced NO_x from the heater without air preheat; but there was no reduction for the heater with air preheat. This type of heater appears more amenable to combustion modification than do natural draft heaters. Also, EPA plans to evaluate the use of in-furnace NO_x reduction, or reburning, on both forced and natural draft refinery process heaters.

Rotary cement kilns produce higher levels of NO_x emissions (100 to 2500 ppm) than do other stationary combustion devices and appear to have a good potential for NO_x reduction by fuel switching and adjustment of operating temperatures. The single burner employed in most units has little provision for adjustment other than excess air levels or burner redesign. Several significant variables affecting NO_x formation in cement kilns have been identified. These are fuel injection velocity, combustion air preheat, furnace wall temperature, carrier gas composition, and excess air. In addition, EPA plans to evaluate the use of in-furnace NO_x reductions (reburning) on cement kilns.

Three steel processing furnaces showed good potential for NO_x reduction by reducing excess air; 40 to 69 percent NO_x reductions were obtained. Removing burners from service on a reheat furnace reduced NO_x by 43 percent. These units should respond well to the use of low NO_x burners and other combustion modifications.

Tests of an aluminum melting furnace indicated premixed burning characteristics; e.g., NO_x increased with decreased excess air. NO_x emissions were found to be relatively low in spite of a hot refractory. The unit tested had a very high stack temperature with good potential for efficiency improvement.

Two boilers burning wood with gas or coal were amenable to air register adjustment, reduced excess air, and burners out of service; NO_x reductions of 15 to 23 percent were observed. Fluctuations in wood flow presented a problem in maintaining stable, repeatable emission levels. A black-liquor recovery boiler tested produced low NO_x emissions at baseline conditions, but CO and HC were high. It was possible to reduce NO_x by 30 percent with secondary air adjustment, but at the expense of higher CO and HC emissions. Combustion modifications are complicated by the complex chemistry of these devices. A boiler burning CO gas showed little response to combustion modifications, attributed to ammonia in the CO gas being converted to NO_x in the same manner as fuel bound nitrogen. Two boilers operating in gas turbine/boiler combined-cycle units responded to burners out of service. Reductions in NO_x of 14 to 38 percent were observed. Only slight changes occurred in thermal efficiency of all units when combustion modifications were applied.

Based on the results of this program, further work has been initiated to investigate, in more detail, the use of combustion modifications on process heaters and cement kilns.

CONCLUSIONS

The data presented show that combustion modification is an effective means to control NO_x emissions for many stationary combustion sources. Depending on equipment type, size, and design and the type of fuel fired, NO_x can be reduced from 10 to 75 percent by combustion modification, with little or no negative effect on other emissions or equipment performance. In order to achieve NO_x reductions greater than 75 percent, it will probably be necessary to use a more costly option; e.g., flue gas treatment.

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